THE RATE OF DENUDATION OF SOME BRITISH LOWLAND LANDSCAPES

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ABSTRACT

Developments in dating techniques applicable to the late Tertiary and Quaternary are giving us the ability to date past land surfaces. Where reasonable assumptions about the nature of such past surfaces and their partial preservation may be made, they can be reconstructed. This permits the contouring and measurement of the subsequent dissection, allowing not only calculation of the average rate of erosion over the elapsed time, but also information on the pattern of incision. Two examples where this has been attempted are present; both are dissected till surfaces in eastern England, one of Anglian and the other of Devensian age. The approach quantifies the disparity between the incision of valleys and the general denudational lowering of the surface which characterizes many landscapes. The technique is not only of academic interest, but potentially forms a useful line of approach to the assessment of the safety of the burying toxic wastes.

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INTRODUCTION

There are two main ways in which we may characterize the evolution of landscapes over time: the incision of rivers to cut valleys, and the overall lowering of the land surface. The rate of river incision may be established from dated terraces or, in appropriate areas, speleothems from dewatered caves (Atkinson and Rowe, 1992). The rate of overall lowering can be established by extrapolating from current rates of erosion, by measuring the volume of dissection below a dated surface, or by measuring the volume of the eroded sediments deposited nearby. Extrapolation from current rates of erosion requires measurements of output (both solid and dissolved discharge) together with the deduction of any inputs in precipitation, but cannot escape from the limitation that present-day conditions include the effects of anthropic disturbance, even in relatively remote areas. There are not many cases where both the form and the age of a dissected surface may be established, but two examples from eastern England are described here; both are areas where till has been deposited by a single ice sheet. The original sheet of till is now dissected by valleys and, by sampling the depth of dissection on a grid pattern, average rates of surface lowering for the entire period can be calculated.

PUBLISHED DATA ON RATES OF DENUDATION

Values for rates of surface lowering have been collated from time to time, the most recent wide-ranging compilation being by Saunders and Young (1983). They collected slope retreat rates and overall rates of denudation from 419 publications world-wide. These were classified by major climatic zone, normal or steep relief, and consolidated or non-consolidated rocks. They generalized the denudation rate data in a figure (Figure 1). The role of vegetation cover in limiting erosion rates is clear, and across the world this is a more important variable than climate *per se*. Part of the wide range of values is linked to overall relief, which controls slope

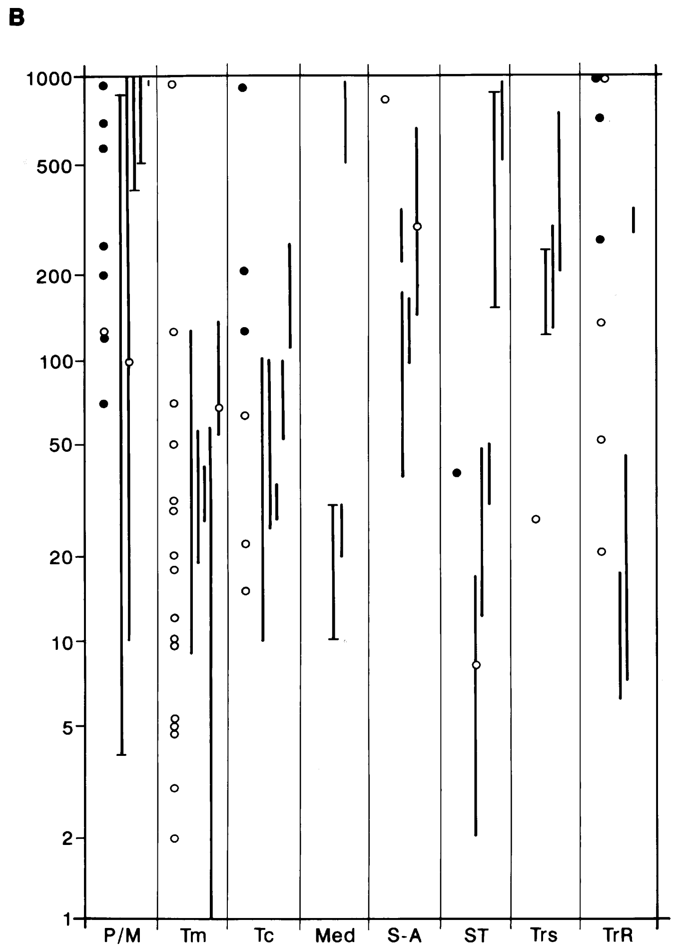

Figure 1. Classification of rates of erosion (after Saunders and Young, 1983). Values are in Bubnoff units (see footnote to Table I). The letters at the bottom indicate climatic classes. The British Isles cases fall within the temperate maritime (Tm) class. Circles indicate single values, lines indicate a range of values in the original source

length and slope angle; this suggests that mountains erode ten times more rapidly than gentle uplands and lowlands.

The values reported from the British Isles are all relatively low, reflecting our humid climate and generally continuous vegetation cover. Indeed, Saunders and Young comment that it 'is ironic that the British Isles, the scene of such a disproportionately large amount of geomorphological research activity, should prove to have such an inactive landscape!' (Saunders and Young, 1983, p. 497). The majority of the published rates they list result from the measurement of a single process and so do not reflect denudation as a whole. On the other hand, in several cases the process measured is so dominant that the value obtained may lie close to the figure for total denudation. This is particularly true for measurements of dissolved load from large limestone outcrops. The available data are summarized in Table I.

The one published value based on the dissection of a land surface over time comes from work by Straw (1979) on the dissection of the glacial landscape of Lincolnshire. He obtained a value presented by Saunders and Young (1983) as 124 B, (Bubnoff unit; 1 B = 1 mm per 1000 years), though inspection of the original suggests 92 B is the proper interpretation of the data provided by Straw. His value is expressed as 3·3 tonne ha^{-1} a^{-1} and is based on the calculation that the volume of denudation since the last deposition of till in the Bain valley of southern Lincolnshire is 360×10^6 m^3 from a basin area of 30 km^2. He believed the glaciation responsible to be the Wolstonian and assigned this an age of 130 ka. This gives a rate of removal of 92 m^3 km^{-2} a^{-1}, a unit which

Table I. Published rates of denudation, British Isles

Area	Reference	Rate (B)*
(a) Lowering by limestone solution		
Southern Pennines	Pitty (1968)	75–83
Fergus Basin, Ireland	Williams (1963)	51
Mendip Hills	Drew (1974)	50–100
(b) Denudation by all processes		
Bain Valley, Lincs	Straw (1979)	92†
Devon	Walling and Webb (1978)	9–125
River Ouse and Adur, Sussex	Collins (1981)	55–132
North Yorks Moors	Arnett (1979)	19–54
River Tyne, Northumberland	Hall (1967)	70–127

* The Bubnoff, whilst not universally popular, has the advantage that it is numerically the same as either the average rate of surface lowering expressed as $mm\,ka^{-1}$, or the rate of removal of material expressed as $m^3\,a^{-1}\,km^{-2}$.
† This value was erroneously reported by Saunders and Young (1983) as 124 B. The value of 92 B reflects Straw's assignment of the till to the Wolstonian; if it is of Anglian age, the rate would be 42 or 25 B. See comment in text.

has the same numerical value as the Bubnoff, so it is not clear how Saunders and Young arrived at their converted figure. However, today many would argue that the till concerned is of Anglian age, and the implications of this on the calculated rate of erosion are discussed below.

Provided that we exclude the most obvious situations where human disturbance has increased the natural rate of erosion, the variability in these figures is less than two orders of magnitude, and if we allow for the measurement of single processes where several must operate, it is perhaps about one order of magnitude. However, these values offer us little information about the magnitude of Quaternary changes. The literature is replete with comments about the variability in past rates of erosion with the climatic changes of the Quaternary. Others speculate (with no direct evidence in most cases and certainly with no support from contemporary rates measured in periglacial areas (e.g. Rapp, 1960)) that past periglacial rates have greatly exceeded contemporary values.

Even if we were ready to extrapolate current values over past time, the range of values would leave us with little guidance. Using the lower values of 10–20 B, mean surface lowering over the *c.* 2 million years of the Quaternary would be 20–40 m; at the upper end of 125–130 B it would be *c.* 250 m. Knowledge of relief, lithology (or rock resistance), net precipitation and degree of disturbance by humans can place some constraints on the likely value, but there is clearly no substitute for direct measurement of landform change if that is feasible.

THE AGE OF BRITISH LANDFORMS

Any full understanding of the long-term evolution of the land surface must rest on satisfactory determination of the rate of change and thus the age of various landforms. One important reason for the shift of interest towards studies of processes was the wholly speculative nature of a denudation chronology without time control.

Gradually, the discovery and dating of remnants of Tertiary sediments has produced new information; for example the work on the Brassington Formation by Walsh *et al.* (1972) and the more recent work on the St. Agnes Formation in Cornwall (Walsh *et al.*, 1987). Increasingly, the availability of reliable dates has placed constraints on the reconstruction of landform evolution and allowed a more secure account of landform change. In addition, a practical requirement for better knowledge of long-term landform evolution has sprung from the need for safe disposal of radioactive wastes. Since these will remain significantly radioactive for at least 100 ka, and the safety analysis may consider changes even beyond this, calculations of past rates of incision are required as a guide to possible future rates. It is not simply that the wastes might be exposed – it is possible to excavate caverns so far below the surface that this can be avoided over the timescale involved – but that changes in surface relief will in turn affect groundwater movement which is the most probable way in which radionuclides might migrate from the underground repository.

THE DISSECTION OF DATED SURFACES

If we are able to reconstruct the original form of a surface before its dissection by rain and rivers, we can construct a map of the depth of subsequent surface lowering from the contours of the land surface today. There are several suitable landscapes of this type, though the surface below which erosion has occurred may not yet be precisely dated in some cases. Examples of suitable landscapes include the lower Thames valley, with a stairway of surfaces identified by remnants of river terraces at several levels above the present floodplain – each terrace represents a former floodplain of the Thames. All the terraces may be dated in terms of the Quaternary chronology of Britain (i.e. in relation to known glacial and interglacial sequences) and some have absolute dates, from ^{14}C or U series. If we correlate the Boyn Hill terrace at Swanscombe with the Hoxnian and thus with Stage 9, then its age will be about 300 ka, if we follow Bowen and Sykes (1988) and adopt their amino acid date, then the correlation is with Stage 11, giving an age of about 400 ka. Thus the rate of incision below the Swanscombe terrace is either 90 or 70 B. Of course, this value for the rate of incision must be greater than the areal rate of denudation or we would not find the Boyn Hill terrace surviving at all.

Other examples include the dissected till surfaces of East Anglia and northern, coastal Northumberland. The latter surface was deposited during (or perhaps more precisely at the end of) the maximum stage of the Devensian Glaciation, *c.* 15 ka BP; the former is the surface of the Anglian till, pre-dating the Hoxnian glaciation. The age of this glaciation is unfortunately not yet completely agreed, and we have to apply two possible dates. The problem is discussed after first reporting the data on denudation. Two areas have been studied and are shown in Figures 2 and 3.

THE DISSECTION OF THE ANGLIAN TILL IN SUFFOLK AND PARTS OF ADJACENT COUNTIES

The base maps utilized are the 1:50 000 sheets of the Ordnance Survey series with metric contours, although in some areas, where the values of subsequent dissection were close to zero, the 1:25 000 maps were also consulted. The area of the main till sheet lying on the southeastward slope of the dip slope of the Chalk was outlined, omitting that part draining northwards towards The Wash. Generalized contours were drawn at 15 m vertical intervals for the till surface by joining with a smoothly curving line the highest contours on each of the main ridges separating the rivers. These interfluves are broad and are believed to lie very close to the original depositional surface of the till. Thus, while the generalized contours must necessarily be drawn boldly across each of the river valleys without any local evidence of their correct position, their position and orientation are strongly constrained by the contours on the broad interfluves, and two or more operators following the same assumption – that the interfluves were close to the original till surface – would produce very similar maps. Further, the low slope of the reconstructed surface (at an average of 2 m km^{-1}) means that any disparities in the location of the reconstructed contours of the till surface have little effect on the final map of denudational lowering. In passing, it is of interest to note that the Anglian till surface in Essex (beyond the area considered here) was contoured almost 40 years ago from the 50 foot contours of the 1:63 360 map and found to have a slope of between 12 and 15 feet per mile (Clayton, 1957, p. 10) or 2·3–2·8 m km^{-1}.

The depth of incision below this reconstructed surface may be determined at every point where the contours of the present land surface cross the reconstructed contours. Additional points may be determined if required by interpolation between the contours (both of the present map and of the reconstructed surface). These points were marked across the whole area of interest and through them were drawn contours of the difference between the initial and the present surface. These have a consistent pattern from one river valley to another, as will be seen from Figure 2. The modal depth of erosion measured over the whole area is 10·46 m. The greatest depths of incision reach almost 60 m, and this maximum value is approached in several of the main river valleys. Because the rivers slope more steeply than the initial surface in their upper reaches and more gently in their lower portions, the contours show greatest depth of downcutting midway down the slope of the surface.

As already noted, the dating of this major glaciation remains uncertain. In U.K. stratigraphical terms it predates the Hoxnian Interglacial, and this is commonly attributed to oxygen isotope Stage 9 (Bowen and Sykes, 1988). Thus the Anglian could be Stage 10, or about 350 ka. However, Bowen and Sykes (1988), using amino acid ratios, attribute part of the Swanscombe deposits (which are also more recent than the Anglian

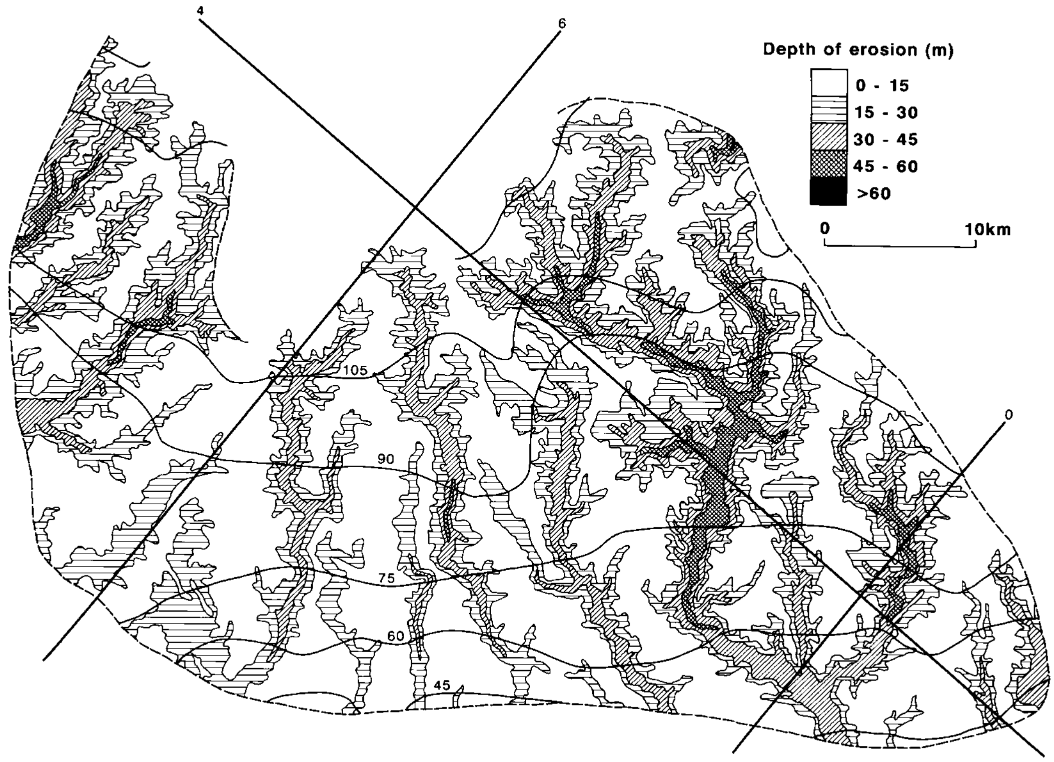

Figure 2. Incision below the reconstructed depositional surface of the Anglian till in Suffolk, England. The heavy contours represent the reconstructed depositional surface of the till; the layer-shaded contours show depths of incision. The effect of adjusting for possible solutional lowering of the interfluves by 4·4 m (see text) has the effect of shifting each contour line about 2 km to the northwest. The grid is the OS National Grid

glaciation) to Stage 11 (i.e. they do not agree with the usual attribution of the Swanscombe terrace sediments to the Hoxnian) and thus place the preceding Anglian at Stage 12. This would give it an age of about 440 ka (Shackleton and Opdyke, 1973). Atkinson and Rowe (1987) attempted to date deposits of this glaciation using U series techniques on carbonate material found near Lowestoft, and got a date of 285 ka (Stage 8), but the materials studied may well have been contaminated. Later work, dating interglacial sediments such as peat and tufa, has been more successful. Dates have now been obtained from interglacial sediments which appear to rest directly on till at three sites. At Tottenhill, peat above Anglian till is dated as Stage 9; at West Stow in Suffolk, tufa above Anglian till is Stage 11 (Rowe, personal communication, 1994). This latter date is supported by the association of the fauna containing the subgenus *Lyrodicus*. At sites across Europe this has been linked with Stage 11. At Hoxne itself dates conflict to some extent, but the most reasonable interpretation is that the interglacial deposits there are of Stage 9 age. Thus part of what is labelled Anglian is most probably Stage 12 in the southern part of East Anglia, though there may have been a later advance in Stage 10 if we are correct in believing there is no time gap between glacial and interglacial layers at Hoxne and Tottenhill. The Anglian glaciation certainly post-dates the Cromerian (Cromer Forest Bed at West Runton) which Bowen and Sykes (1988) correlate with Stage 13. Thus we seem to be left with a most probable date of Stage 12 (440 ka) and a possible date of Stage 10 (350 ka); both dates are used in the discussion which follows.

The maximum depth of valley incision (59·6 m) represents a time-averaged rate of incision of 136 B if we use the value of 440 ka (Stage 12) for the Anglian glaciation, and 170 B if we use the Stage 10 value of 350 ka. The areal average rate of denudation is much lower than the calculated time-average rate of valley incision, as the interfluves have been little reduced below the original surface. Sampling the pattern of Figure 2 on a regular

(1 km) grid with 2235 points gives an average lowering of 16·91 m, i.e. about 38 B if we use the Stage 12 date, or 48 B if we use the Stage 10 date.

We may compare the values in Table II with the recalculated values for the Bain valley, Lincolnshire (Straw, 1979). The value of 92 B, based on data provided by Straw, for the dissection of the till in the Bain valley (Lincolnshire) would be reduced if the chalky boulder clay were of Anglian age, as many would currently argue (Bowen *et al*., 1986). Correlation of the Anglian with oxygen isotope Stage 12 brings the average rate of denudation down to 27 B. It is possible (if the peat at Tottenhill immediately post-dates the underlying till) that the apparently Anglian till of southern Lincolnshire is of Stage 10 age, since this would produce a rate for Lincolnshire of 34 B and, on the same basis, a Stage 12 age for the Suffolk till would produce a rate of 38 B, the results are then very similar and may give some support to this interpretation.

The validity of this reconstruction rests on whether the highest parts of the interfluves are close to the original surface of the glacial deposits. In Northumberland this is likely, since constructional glacial forms persist. The absence of such forms in Suffolk allows the hypothesis that an original surface (e.g. with drumlins) has been smoothed and destroyed by subsequent denudation. There can be no certainty on this point, though it should be noted that smooth till surfaces are often produced by ice sheets, and such surfaces of Last Glacial age are quite common in Poland and elsewhere, where they evoke no comment or surprise. In Suffolk, the broader interfluves have contours which follow the alignment of the generalized contours, suggesting that, at the very least, the original direction of slope has survived, and this conclusion is reinforced by the match between the river directions and the reconstructed slope. If an original, more irregular, surface has been modified after deglaciation, it must have been smoothed more than it was lowered or the irregularities left by the ice would not have been extinguished. Such smoothing would redistribute material from crests to hollows, which does not necessarily contribute to overall lowering.

In a peer review of this work (as part of the Nirex Quality Assurance Procedure), J. A. Catt commented that the reconstructed surface must fall some little way below the original till surface at all points, as Hoxnian interglacial soils have not survived on the interfluves. This observation implies that even the flattest parts of the interfluves have lost soil cover (and had some wind-blown silt added), but the total lowering need not be large in order to lose the interglacial soil. With an average lowering of 16·9 m, we may thus be *underestimating* the total lowering by a few metres or up to 25 per cent. It is unlikely to be more or we would not find the surviving summits on the major interfluves fitting an even slope so well. In addition, as was suggested for the till surface in Essex (Clayton, 1960, p. 63), the main rivers locally follow subglacial valleys and must have located over these as a result of local sagging, perhaps due to consolidation of the thicker sediments over these preglacial or subglacial valleys. This would cause us to *overestimate* the total denudation, though probably by no more than 10 per cent. Thus the figure we calculate here is best regarded as a slight underestimate, though probably by no more than 10–15 per cent.

Reflecting on the comment of Catt that there are no surviving interglacial soils, we should also note that invariably the soil formed on the chalky boulder clay is free of chalk, so some lowering by solution has undoubtedly occurred. Solution is concentrated at the soil/rock interface and probably increases downslope as water moves under the influence of gravity in the surface regolith, so we may reasonably regard it has having operated over the entire surface. Contemporary values from Norfolk rivers (Edwards, 1973) are annual rates of removal of calcium carbonate (allowing for rainfall inputs) of 58·0 tonne km^{-2} for the Yare and 39·2 tonne km^{-2} for the Tud. These translate to rates (for $CaCO_3$ alone) of 22 and 15 B. Long-term values are probably lower, so a value of 10 B is taken, implying overall surface lowering by solution of 4·4 m. In the circumstances it seems a reasonable basis by which to adjust the Suffolk data reported here; however, its impact on Northumberland is minimal, not so much because of the smaller calcareous content of the tills and underlying rocks, but because of the very short time involved.

The effect of this addition (to both the average depth of erosion and to the maximum depth of incision) is to increase the rate of denudation, adopting the Stage 12 age, from 38·4 to 48·4 B and the rate of incision from 135 to 145 B (Table II).

It will be noted that the values for the rate of incision (whether based on the younger or older age) are greater than the two alternative values for the Boyn Hill terrace of the Thames at Swanscombe (70 or 90 B). Two factors may be involved. The valley floor at Swanscombe is occupied by the tidal Thames, so the depth of incision

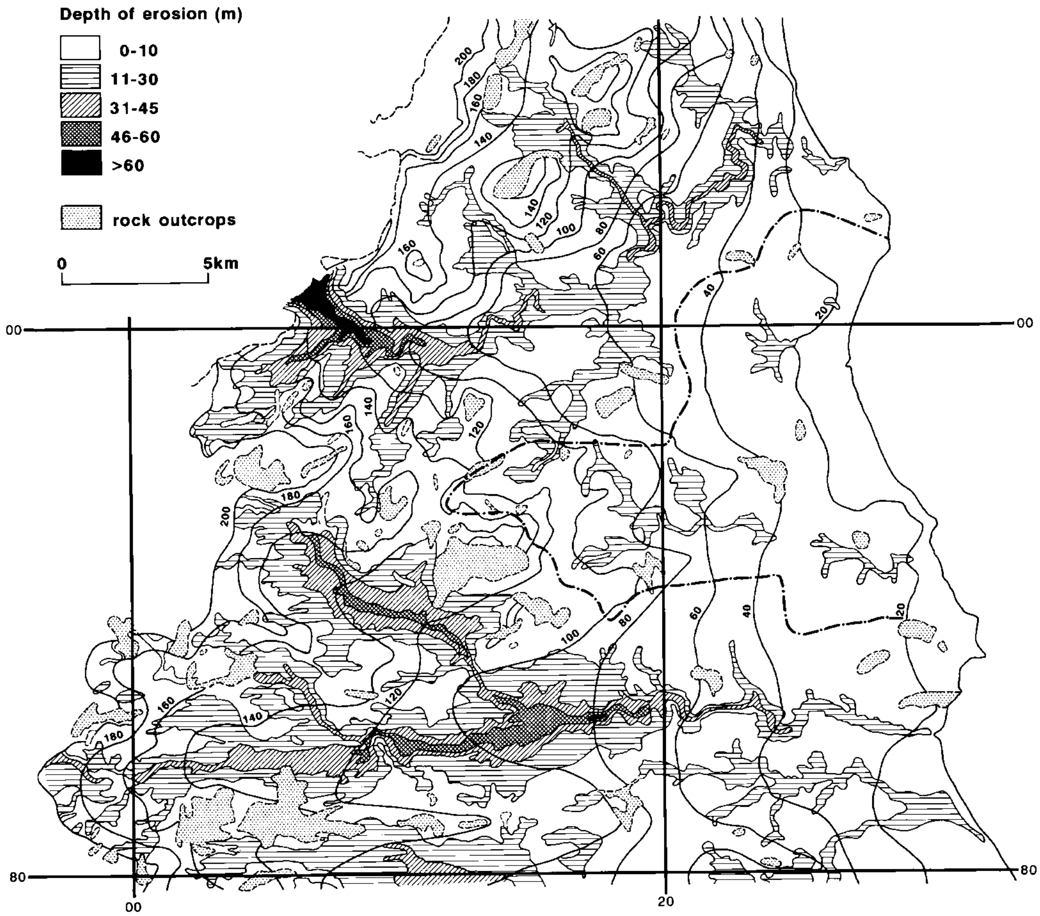

Figure 3. Incision below the reconstructed depositional surface of the Devensian till of part of Northumberland, England. The heavy contours represent the reconstructed depositional surface of the till; the layer-shaded contours show depths of incision. The area where the rivers rise on the till surface (see Table II) is outlined by a dash-dot line. The grid is the OS National Grid

Table II. Data for Anglian Till, Suffolk

	Original measurements	With overall solutional lowering of 4·4 m
Number of data points	2325	2325
Average depth of erosion	16·91 m	21·31 m
Modal depth of erosion	10·46 m	14·86 m
Maximum depth of incision	59·6 m	64 m
Max. rate of incision (350 ka)	170 B	180 B
Rate of erosion (350 ka)	48·3 B	58·3 B
Max. rate of incision (440 ka)	135 B	145 B
Rate of erosion (440 ka)	38·4 B	48·4 B

today is limited by contemporary sea level; secondly, the lower Thames valley is an area of recent subsidence (e.g. as indicated by the level of Roman salt pans and other signs of settlement below present sea level) and this has probably occurred over much of the period we are considering, so reducing the measured depth of incision. We may note that incision at Goring Gap, subsequent to the formation of the terrace which predates the Anglian glaciation, is some 55 m (extracted from Figure 3 of Whiteman and Rose, 1992), agreeing well with the values for the largest valleys in Suffolk.

THE DISSECTION OF THE DEVENSIAN TILL IN NORTHUMBERLAND

Figure 3 shows the depth of incision below the Northumberland till surface immediately west of the coast and north of the River Tyne. The situation is rather different from Suffolk in several ways. The till sheet does not fully clothe the solid rocks (largely resistant sandstones of Middle and Lower Carboniferous age) and these appear through the till at a number of points. To the west, the till sheet lies against the rising ground towards the Cheviot Hills, and steeper slopes on solid rock (or on discontinuous till lying above the solid rocks) limit the area where reconstruction is possible. The greatest contrast stems from the rivers which rise beyond the till sheet to cross it to the sea. These are more deeply incised than the Suffolk valleys, reflecting the effect of the high discharges achieved in the upper catchments in the high hills to the west. In an area occupying just over one-third of the entire area sampled, the streams rise on the till sheet (the Lyne basin and small adjacent streams to the north), so matching more closely the Suffolk situation.

As will be seen by comparing values in Tables II and III, the average rate of erosion for the whole Northumberland area sampled is 21 times that of Suffolk. The ratio for the area entirely on till (Table II, column 2) is 16. However, the small length of the streams in this area of 121 km^2 will have an impact: for example, the upper 95 km^2 of the Upper Roding valley in Essex has an average depth of erosion of 15·29 m compared with the average of about 21 m for the whole area surveyed. Applying the same ratio to the Lyne valley data implies an average for a larger area of 7·9 m. This average depth of erosion is the value obtained by eliminating the very deep valleys that come off the Cheviots, where values of incision exceed 22 m. The values for the area calculated on this basis appear in the last column of Table III and probably provide the best comparison with the Suffolk situation. Inevitably, in addition to age, there are other differences between Northumberland and Suffolk; the till surface in the former slopes at 3·5 m km^{-1} and annual rainfall is 700 mm, compared with 600 mm in Suffolk.

Table III. Northumberland (Devensian) till

Number of data points	336	121	275
Average depth of incision	11·85 m	4·3 m	7·8 m
Modal depth of incision	7·46 m	1·0 m	7·46 m
Maximum depth of incision	47·1 m	18·4 m	22·0 m
Max. rate of incision (15 ka)	3140 B	1227 B	1467 B
Rate of erosion (15 ka)	790 B	287 B	520 B

THE RELATIONSHIP BETWEEN THE RATE OF VALLEY INCISION AND OVERALL RATES OF DENUDATION

The maximum, or indeed the mean, depth of valley incision will always exceed the average denudational lowering below a reconstructed initial surface. The Suffolk and Northumberland data show that the difference can be large: in each case, the maximum depth of valley incision is more than three times the average rate measured over the landscape as a whole.

This distinction between valley incision (I) and overall denudation (D) has of course been made before, most notably by the Pencks (conveniently quoted by Beckinsale and Chorley, 1991, pp. 327–344). Albrecht Penck used this distinction between valley incision and overall denudation in his analysis of landform development, and the idea was also used by his son Walther in his approach to landform evolution over time. It should be noted that the ratio I/D can be determined for any landscape for which it is possible to infer an original surface, even where the surface is not dated. It seems likely that a decrease in the I/D ratio will accompany increasingly mature landscapes in the Davisian scheme of landform development, while the ratio should remain constant (at 1·00) in the ideal Hackian landscape. The actual ratio for the Northumberland till is 3·97 and for Suffolk 3·04. Decline from the younger to the older till is what we would expect (since incision into a planar initial surface is 'Davisian'), although we cannot place much weight on only two values.

The overall geometry of the dissected surfaces in Northumberland and Suffolk reflects the spacing of the major streams and the pattern of the tributaries, which is in turn a result of the degree to which a truly dendritic

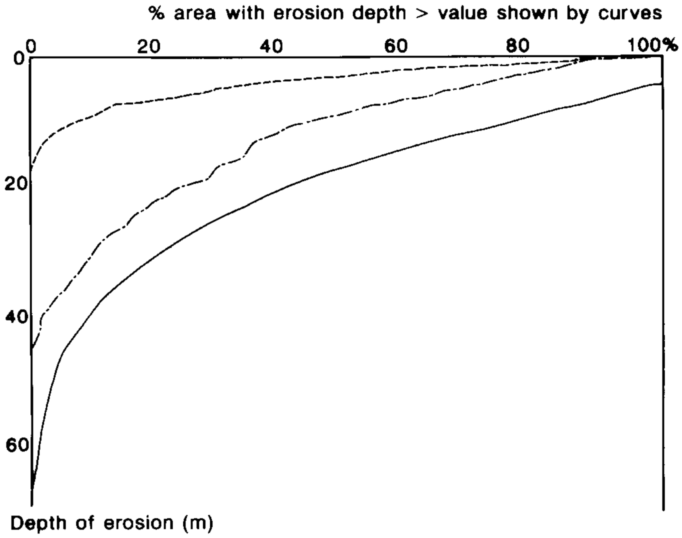

Figure 4. Cumulative amounts of lowering below the original depositional surface of till of Devensian and Anglian age in eastern England. The dashed line represents 121 km^2 of adjacent basins draining direct to the North Sea on the Devensian till (*c.* 15 ka BP) in Northumberland; the dot-dash line is derived from 336 data points covering a wider area (336 km^2) of the coastal margin of northern Northumberland. The solid line is derived from 2325 km^2 of the Anglian till (*c.* 440 ka) on the Chalk dipslope of Suffolk and northeastern Essex, and includes the allowance of 4·4 m for solutional lowering of the whole land surface

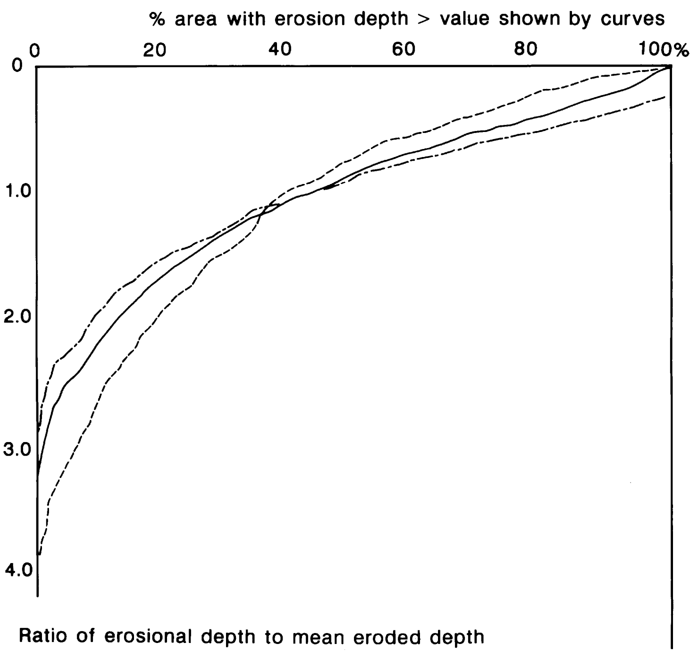

Figure 5. Dimensionless graphs of denudation/depth frequency for the Suffolk Anglian till and the Northumberland Devensian till. Dimensionless plots of the original Suffolk (solid line) and the complete Northumberland (dashed line) data. The dot-dash line for Suffolk includes the allowance of 4·4 m for overall solutional lowering.

drainage has developed. However, we may compare the geometry at a higher level of abstraction by plotting the frequency distribution of cumulative depth of erosion. This has been done in Figures 4 and 5 and it will be seen

that the two curves are remarkably similar in shape, the smoother Suffolk curve reflecting both the large number of data points and perhaps also the longer time over which the surface has developed. If we scale the Suffolk curve in Figure 5 by the average spacing of the major rivers (6 km), then we have the average form of the valley slopes, with both vertical (depth of incision 60 m) and horizontal (3 km) control. The strongly convex slope of both curves reflects the I/D ratio and indicates the nature of the spatial pattern and depth of denudation. The small number of high values reflects the limited development of valley-floor flats and floodplains, a result of the limited discharge from small basins and the geomorphologically short period of time this landscape has had to evolve.

By including the allowance for solutional lowering of the almost level interfluves in Figure 4, the curve runs up towards the interfluves with less convergence to the Northumberland line. The relationship on the dimensionless curve (Figure 5) also shows a greater parallelism away from the main valleys, so we may adduce some support for the concept here, though the approach cannot determine whether or not 4·4 m is a reasonable approximation.

The total erosion for the Northumberland till recorded by the full set of values (i.e. an average depth of erosion of 11·51 m) is perfectly real. It demonstrates the speed of initial incision of rivers into a new landscape, especially where discharges are relatively high. Thus the rate of 790 B may be rather higher than for Suffolk in its first 15 ka: nonetheless, we can envisage something like an average of 8 m ground surface lowering in this period. If this figure is regarded as a feasible value for the first 15 ka of erosion, when stream incision is most rapid, it can be applied to the Suffolk till values, leaving a residual rate of 42·5 B for the subsequent 335 ka (Stage 10) or 31·3 B for the following 425 ka if the date is Stage 12. Rapid initial change of a young landscape, followed by slower evolution, has been noted by a number of authors, including the observations of Ruhe (1952) in the U.S. Mid-West, though the 'topographic discontinuities' he describes are derived from contrasts in drainage development, effectively a surrogate for incision so far as this comparison is concerned. In an earlier paper (Ruhe, 1950) he measures frequency curves for percentage slope on five different tills, but these cannot readily be linked with the data obtained from this study. It is also worth recalling that Straw (1979) noted that the Bain valley must have changed in the past more rapidly than his average value, since very little change occured during the Holocene.

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